

## **AUGMENTATION OF ELECTRICAL CONDUCTION AND CONTRACTILITY BY BIPHASIC CARDIAC PACING ADMINISTERED VIA THE CARDIAC BLOOD POOL**

### **CROSS REFERENCE TO RELATED APPLICATIONS**

**[0001]** This application is a continuation of U.S. patent application no. 09/690,947, filed October 18, 2000, pending, which is a continuation-in-part of U.S. patent application no. 09/008,636 filed January 16, 1998, now U.S. Patent no. 6,136,019, which is a continuation-in-part of U.S. patent application no. 08/699,552, filed August 19, 1996, now U.S. Patent no. 5,871,506. The 09/690,947, 09/008,636, and 08/699,552 applications are all incorporated by reference herein, in their entirety, for all purposes.

### **FIELD OF THE INVENTION**

**[0002]** This invention relates generally to a method for the stimulation of muscle tissue. In particular, this invention relates to a method for cardiac stimulation and pacing with biphasic waveforms wherein the stimulation is administered via the cardiac blood pool.

### **BACKGROUND OF THE INVENTION**

**[0003]** The function of the cardiovascular system is vital for survival. Through blood circulation, body tissues obtain necessary nutrients and oxygen, and discard waste substances. In the absence of circulation, cells begin to undergo irreversible changes that lead to death. The muscular contractions of the heart are the driving force behind circulation.

**[0004]** In cardiac muscle, the muscle fibers are interconnected in branching networks that spread in all directions through the heart. When any portion of this net is stimulated, a depolarization wave passes to all of its parts and the entire structure contracts as a unit. Before a muscle fiber can be stimulated to contract, its membrane must be polarized. A muscle fiber generally remains polarized until it is stimulated by some change in its environment. A membrane can be stimulated electrically, chemically, mechanically or by temperature change. The minimal stimulation strength needed to elicit a contraction is known as the threshold stimulus. The maximum stimulation amplitude that may be administered without eliciting a contraction is the maximum subthreshold amplitude.

[0005] Where the membrane is stimulated electrically, the impulse amplitude required to elicit a response is dependent upon a number of factors. First, is the duration of current flow. Since the total charge transferred is equal to the current amplitude times the pulse duration, increased stimulus duration is associated with a decrease in threshold current amplitude. Second, the percentage of applied current that actually traverses the membrane varies inversely with electrode size. Third, the percentage of applied current that actually traverses the membrane varies directly with the proximity of the electrode to the tissue. Fourth, the impulse amplitude required to elicit a response is dependent upon the timing of stimulation within the excitability cycle.

[0006] Throughout much of the heart are clumps and strands of specialized cardiac muscle tissue. This tissue comprises the cardiac conduction system and serves to initiate and distribute depolarization waves throughout the myocardium. Any interference or block in cardiac impulse conduction may cause an arrhythmia or marked change in the rate or rhythm of the heart.

[0007] Sometimes a patient suffering from a conduction disorder can be helped by an artificial pacemaker. Such a device contains a small battery powered electrical stimulator. When the artificial pacemaker is installed, electrodes are generally threaded through veins into the right ventricle, or into the right atrium and right ventricle, and the stimulator is planted beneath the skin in the shoulder or abdomen. The leads are planted in intimate contact with the cardiac tissue. The pacemaker then transmits rhythmic electrical impulses to the heart, and the myocardium responds by contracting rhythmically. Implantable medical devices for the pacing of the heart are well known in the art and have been used in humans since approximately the mid 1960s.

[0008] Either cathodal or anodal current may be used to stimulate the myocardium. However anodal current is thought not to be useful clinically. Cathodal current comprises electrical pulses of negative polarity. This type of current depolarizes the cell membrane by discharging the membrane capacitor, and directly reduces the membrane potential toward threshold level. Cathodal current, by directly reducing the resting membrane potential toward threshold has a one-half to one-third lower threshold current in late diastole than does anodal current. Anodal current comprises electrical pulses of positive polarity. The effect of anodal current is to hyperpolarize the resting membrane. On

sudden termination of the anodal pulse, the membrane potential returns towards resting level, overshoots to threshold, and a propagated response occurs. The use of anodal current to stimulate the myocardium is generally discouraged due to the higher stimulation threshold, which leads to use of a higher current, resulting in a drain on the battery of an implanted device and impaired longevity. Additionally, the use of anodal current for cardiac stimulation is discouraged due to the suspicion that the anodal contribution to depolarization can, particularly at higher voltages, contribute to arrhythmogenesis.

[0009] Virtually all artificial pacemaking is done using stimulating pulses of negative polarity, or in the case of bipolar systems, the cathode is closer to the myocardium than is the anode. Where the use of anodal current is disclosed, it is generally as a charge of minute magnitude used to dissipate residual charge on the electrode. This does not affect or condition the myocardium itself. Such a use is disclosed in U.S. Patent No. 4,543,956 to Herscovici.

[0010] In using a triphasic waveform, the first and third phases have nothing to do with the myocardium *per se*, but are only envisioned to affect the electrode surface itself. Thus, the charge applied in these phases is of very low amplitude. Disclosures relevant to this practice are found in U.S. Patent Nos. 4,903,700 and 4,821,724 to Whigham *et al.*, and U.S. Patent No. 4,343,312 to Cals *et al.*.

[0011] Lastly, biphasic stimulation has been used to produce voltage doubling without the need for a large capacitor in the output circuit. The phases of the biphasic stimulation disclosed are of equal magnitude and duration. Refer to U.S. Patent No. 4,402,322 to Duggan for details.

[0012] What is needed is an improved means for stimulating muscle tissue, wherein the contraction elicited is enhanced and the damage to the tissue adjacent to the electrode is diminished.

[0013] Enhanced myocardial function is obtained through the biphasic pacing of the present invention. The combination of cathodal with anodal pulses, of either a stimulating or conditioning nature, preserves the improved conduction and contractility of anodal pacing while eliminating the drawback of increased stimulation threshold. The result is a depolarization wave of increased propagation speed. This increased propagation speed

results in superior cardiac contraction leading to an improvement in blood flow. Improved stimulation at a lower voltage level also results in reduction in power consumption and increased life for pacemaker batteries. Lastly, the improved stimulation achieved through the practice of the present invention allows for cardiac stimulation without the necessity of placing electrical leads in intimate contact with cardiac tissue. Standard stimuli delivered to the cardiac blood pool are ineffective in capturing the myocardium because it does not meet the stimulation threshold. While voltage of the pulse generator can be increased, when it does capture it is often so high that it also stimulates skeletal muscles thereby causing a painful twitching of the chest wall when only the heart stimulation was desired. As will be further discussed, through the practice of the present invention, one can enhance myocardial function through cardiac blood pool stimulation.

[0014] As with the cardiac muscle, striated muscle may also be stimulated electrically, chemically, mechanically or by temperature change. Where the muscle fiber is stimulated by a motor neuron, the neuron transmits an impulse that activates all of the muscle fibers within its control, that is, those muscle fibers in its motor unit. Depolarization in one region of the membrane stimulates adjacent regions to depolarize also, and a wave of depolarization travels over the membrane in all directions away from the site of stimulation. Thus, when a motor neuron transmits an impulse, all the muscle fibers in its motor unit are stimulated to contract simultaneously. The minimum strength to elicit a contraction is called the threshold stimulus. Once this level of stimulation has been met, the generally held belief is that increasing the level will not increase the contraction. Additionally, since the muscle fibers within each muscle are organized into motor units, and each motor unit is controlled by a single motor neuron, all of the muscle fibers in a motor unit are stimulated at the same time. However, the whole muscle is controlled by many different motor units that respond to different stimulation thresholds. Thus, when a given stimulus is applied to a muscle, some motor units may respond while others do not.

[0015] The combination of cathodal and anodal pulses of the present invention also provides improved contraction of striated muscle where electrical muscular stimulation is indicated due to neural or muscular damage. Where nerve fibers have been damaged due to trauma or disease, muscle fibers in the regions supplied by the damaged nerve fiber tend to undergo atrophy and waste away. A muscle that cannot be exercised may decrease to

half of its usual size in a few months. Where there is no stimulation, not only will the muscle fibers decrease in size, but also they will become fragmented and degenerated, and replaced by connective tissue. Through electrical stimulation one may maintain muscle tone, such that upon healing or regeneration of the nerve fiber, viable muscle tissue remains. Enhanced muscle contraction is obtained through the biphasic stimulation of the present invention. The combination of cathodal with anodal pulses of either a stimulating or conditioning nature results in contraction of a greater number of motor units at a lower voltage level, leading to superior muscle response.

#### **SUMMARY OF THE INVENTION**

[0016] It is therefore an object of the present invention to provide improved stimulation of cardiac tissue.

[0017] It is another object of the present invention to increase cardiac output through superior cardiac contraction leading to greater stroke volume.

[0018] It is another object of the present invention to increase impulse propagation speed.

[0019] It is another object of the present invention to extend pacemaker battery life.

[0020] It is a further object of the present invention to obtain effective cardiac stimulation at a lower voltage level.

[0021] It is a further object of the present invention to eliminate the necessity of placing electrical leads in intimate contact with tissue to obtain tissue stimulation.

[0022] It is a further object of the present invention to provide improved stimulation of muscle tissue.

[0023] It is a further object of the present invention to provide contraction of a greater number of muscle motor units at a lower voltage level.

[0024] A method and apparatus for muscular stimulation in accordance with the present invention includes the administration of biphasic stimulation to the muscle tissue, wherein both cathodal and anodal pulses are administered. According to one aspect of this invention, this stimulation is administered to the myocardium in order to enhance myocardial function. According to a further aspect of this invention, this stimulation is administered to the cardiac blood pool and thereafter conducted to the cardiac tissue. This

enables cardiac stimulation without the necessity of placing electrical leads in intimate contact with cardiac tissue. According to a still further aspect of this invention, the stimulation is administered to striated muscle tissue to evoke muscular response.

Pacemaker electronics needed to practice the method of the present invention are well known to those skilled in the art. Current pacemaker electronics are capable of being programmed to deliver a variety of pulses, including those disclosed herein.

**[0025]** The method and apparatus of the present invention comprises a first and second stimulation phase, with each stimulation phase having a polarity, amplitude, shape and duration. In a preferred embodiment the first and second phases have differing polarities. In one alternative embodiment, the two phases are of differing amplitude. In a second alternative embodiment, the two phases are of differing duration. In a third alternative embodiment, the first phase is in a chopped waveform. In a fourth alternative embodiment, the amplitude of the first phase is ramped. In a fifth alternative embodiment the first phase is administered over 200 milliseconds after completion of a cardiac beating/pumping cycle. In a preferred alternative embodiment, the first phase of stimulation is an anodal pulse at maximum subthreshold amplitude for a long duration, and the second phase of stimulation is a cathodal pulse of short duration and high amplitude. It is noted that the aforementioned alternative embodiments can be combined in differing fashions. It is also noted that these alternative embodiments are intended to be presented by way of example only, and are not limiting.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0026]** Fig. 1 is a schematic representation of leading anodal biphasic stimulation.

**[0027]** Fig. 2 is a schematic representation of leading cathodal biphasic stimulation.

**[0028]** Fig. 3 is a schematic representation of leading anodal stimulation of low level and long duration, followed by conventional cathodal stimulation.

**[0029]** Fig. 4 is a schematic representation of leading anodal stimulation of ramped low level and long duration, followed by conventional cathodal stimulation.

**[0030]** Fig. 5 is a schematic representation of leading anodal stimulation of low level and short duration, administered in series followed by conventional cathodal stimulation.

[0031] Fig. 6 graphs conduction velocity transverse to the fiber vs. pacing duration resulting from leading anodal biphasic pulse.

[0032] Fig. 7 graphs conduction velocity parallel to the fiber vs. pacing duration resulting from leading anodal biphasic pulse.

[0033] Fig. 8 illustrates a schematic view of a cardiac stimulator according to one embodiment of the present invention.

#### **DETAILED DESCRIPTION OF THE INVENTION**

[0034] The present invention relates to the biphasic electrical stimulation of muscle tissue. Fig. 1 depicts biphasic electrical stimulation wherein a first stimulation phase comprising anodal stimulus **102** is administered having amplitude **104** and duration **106**. This first stimulation phase is immediately followed by a second stimulation phase comprising cathodal stimulation **108** of equal intensity and duration.

[0035] Fig. 2 depicts biphasic electrical stimulation wherein a first stimulation phase comprising cathodal stimulation **202** having amplitude **204** and duration **206** is administered. This first stimulation phase is immediately followed by a second stimulation phase comprising anodal stimulation **208** of equal intensity and duration.

[0036] Fig. 3 depicts a preferred embodiment of the present invention wherein a first stimulation phase comprising low level, long duration anodal stimulation **302** having amplitude **304** and duration **306** is administered. This first stimulation phase is immediately followed by a second stimulation phase comprising cathodal stimulation **308** of conventional intensity and duration. In an alternative embodiment of the invention, anodal stimulation **302** is at maximum subthreshold amplitude. In yet another alternative embodiment of the invention, anodal stimulation **302** is less than three volts. In another alternative embodiment of the invention, anodal stimulation **302** is a duration of approximately two to eight milliseconds. In yet another alternative embodiment of the invention, cathodal stimulation **308** is of a short duration. In another alternative embodiment of the invention, cathodal stimulation **308** is approximately 0.3 to 0.8 milliseconds. In yet another alternative embodiment of the invention, cathodal stimulation **308** is of a high amplitude. In another alternative embodiment of the invention, cathodal stimulation **308** is in the approximate range of three to twenty volts. In yet another

alternative embodiment of the present invention, cathodal stimulation **308** is of a duration less than 0.3 milliseconds and at a voltage greater than twenty volts. In another alternative embodiment, anodal stimulation **302** is administered over 200 milliseconds post heart beat. In the manner disclosed by these embodiments, as well as those alterations and modifications that may become obvious upon the reading of this specification, a maximum membrane potential without activation is achieved in the first phase of stimulation.

[0037] Fig. 4 depicts an alternative preferred embodiment of the present invention wherein a first stimulation phase comprising anodal stimulation **402** is administered over period **404** with rising intensity level **406**. The ramp of rising intensity level **406** may be linear or non-linear, and the slope may vary. This anodal stimulation is immediately followed by a second stimulation phase comprising cathodal stimulation **408** of conventional intensity and duration. In an alternative embodiment of the invention, anodal stimulation **402** rises to a maximum subthreshold amplitude. In yet another alternative embodiment of the invention, anodal stimulation **402** rises to a maximum amplitude that is less than three volts. In another alternative embodiment of the invention, anodal stimulation **402** is a duration of approximately two to eight milliseconds. In yet another alternative embodiment of the invention, cathodal stimulation **408** is of a short duration. In another alternative embodiment of the invention, cathodal stimulation **408** is approximately 0.3 to 0.8 milliseconds. In yet another alternative embodiment of the invention, cathodal stimulation **408** is of a high amplitude. In another alternative embodiment of the invention, cathodal stimulation **408** is in the approximate range of three to twenty volts. In yet another alternative embodiment of the present invention, cathodal stimulation **408** is of a duration less than 0.3 milliseconds and at a voltage greater than twenty volts. In another alternative embodiment, anodal stimulation **402** is administered over 200 milliseconds post heart beat. In the manner disclosed by these embodiments as well as those alterations and modifications which may become obvious upon the reading of this specification, a maximum membrane potential without activation is achieved in the first phase of stimulation.

[0038] Fig. 5 depicts biphasic electrical stimulation wherein a first stimulation phase comprising series **502** of anodal pulses is administered at amplitude **504**. In one embodiment rest period **506** is of equal duration to stimulation period **508** and is

administered at baseline amplitude. In an alternative embodiment, rest period **506** is of a differing duration than stimulation period **508** and is administered at baseline amplitude. Rest period **506** occurs after each stimulation period **508** with the exception that a second stimulation phase comprising cathodal stimulation **510** of conventional intensity and duration immediately follows the completion of series **502**. In an alternative embodiment of the invention, the total charge transferred through series **502** of anodal stimulation is at the maximum subthreshold level. In yet another alternative embodiment of the invention, the first stimulation pulse of series **502** is administered over 200 milliseconds post heart beat. In another alternative embodiment of the invention, cathodal stimulation **510** is of a short duration. In yet another alternative embodiment of the invention, cathodal stimulation **510** is approximately 0.3 to 0.8 milliseconds. In another alternative embodiment of the invention, cathodal stimulation **510** is of a high amplitude. In yet another alternative embodiment of the invention, cathodal stimulation **510** is in the approximate range of three to twenty volts. In another alternative embodiment of the invention, cathodal stimulation **510** is of a duration less than 0.3 milliseconds and at a voltage greater than twenty volts.

#### EXAMPLE 1

[0039] Stimulation and propagation characteristics of the myocardium were studied in isolated hearts using pulses of differing polarities and phases. The experiments were carried out in five isolated Langendorff perfused rabbit hearts. Conduction velocity on the epicardium was measured using an array of bipolar electrodes. Measurements were made between six millimeters and nine millimeters from the stimulation site. Transmembrane potential was recorded using a floating intracellular microelectrode. The following protocols were examined: monophasic cathodal pulse, monophasic anodal pulse, leading cathodal biphasic pulse and leading anodal biphasic pulse.

[0040] Table 1 discloses the conduction speed transverse to fiber direction for each stimulation protocol administered, with stimulations of three, four and five volts and two millisecond pulse duration.

TABLE 1

Conduction Speed Transverse to Fiber Direction, 2 msec duration

	3 V	4 V	5 V
Cathodal Monophasic	18.9 ± 2.5 cm/sec	21.4 ± 2.6 cm/sec	23.3 ± 3.0 cm/sec
Anodal Monophasic	24.0 ± 2.3 cm/sec	27.5 ± 2.1 cm/sec	31.3 ± 1.7 cm/sec
Leading Cathodal Biphasic	27.1 ± 1.2 cm/sec	28.2 ± 2.3 cm/sec	27.5 ± 1.8 cm/sec
Leading Anodal Biphasic	26.8 ± 2.1 cm/sec	28.5 ± 0.7 cm/sec	29.7 ± 1.8 cm/sec

[0041] Table 2 discloses the conduction speed along fiber direction for each stimulation protocol administered, with stimulations of three, four and five volts and two millisecond pulse duration.

TABLE 2

Conduction Speed Along Fiber Direction, 2 msec stimulation

	3 V	4 V	5 V
Cathodal Monophasic	45.3 ± 0.9 cm/sec	47.4 ± 1.8 cm/sec	49.7 ± 1.5 cm/sec
Anodal Monophasic	48.1 ± 1.2 cm/sec	51.8 ± 0.5 cm/sec	54.9 ± 0.7 cm/sec
Leading Cathodal Biphasic	50.8 ± 0.9 cm/sec	52.6 ± 1.1 cm/sec	52.8 ± 1.7 cm/sec
Leading Anodal Biphasic	52.6 ± 2.5 cm/sec	55.3 ± 1.5 cm/sec	54.2 ± 2.3 cm/sec

[0042] The differences in conduction velocities between the cathodal monophasic, anodal monophasic, leading cathodal biphasic and leading anodal biphasic were found to be significant ( $p < 0.001$ ). From the transmembrane potential measurements, the maximum upstroke ( $(dV/dt)_{max}$ ) of the action potentials was found to correlate well with the changes in conduction velocity in the longitudinal direction. For a four volt pulse of two millisecond duration,  $(dV/dt)_{max}$  was  $63.5 \pm 2.4$  V/sec for cathodal and  $75.5 \pm 5.6$  V/sec for anodal pulses.

## EXAMPLE 2

[0043] The effects of varying pacing protocols on cardiac electrophysiology were analyzed using Langendorff prepared isolated rabbit hearts. Stimulation was applied to the heart at a constant voltage rectangular pulse. The following protocols were examined: monophasic anodal pulse, monophasic cathodal pulse, leading anodal biphasic pulse and leading cathodal biphasic pulse. Administered voltage was increased in one volt steps from one to five volts for both anodal and cathodal stimulation. Duration was increased in two millisecond steps from two to ten milliseconds. Epicardial conduction velocities were

measured along and transverse to the left ventricular fiber direction at a distance between three to six millimeters from the left ventricular free wall. Figs. 6 and 7 depict the effects of stimulation pulse duration and the protocol of stimulation administered on the conduction velocities.

[0044] Fig. 6 depicts the velocities measured between three millimeters and six millimeters transverse to the fiber direction. In this region, cathodal monophasic stimulation **602** demonstrates the slowest conduction velocity for each stimulation pulse duration tested. This is followed by anodal monophasic stimulation **604** and leading cathodal biphasic stimulation **606**. The fastest conductive velocity is demonstrated by leading anodal biphasic stimulation **608**.

[0045] Fig. 7 depicts the velocities measured between three millimeters and six millimeters parallel to the fiber direction. In this region, cathodal monophasic stimulation **702** demonstrates the slowest conduction velocity for each stimulation pulse duration tested. Velocity results of anodal monophasic stimulation **704** and leading cathodal biphasic stimulation **706** are similar with anodal monophasic stimulation demonstrating slightly quicker speeds. The fastest conduction velocity is demonstrated by leading anodal biphasic stimulation **708**.

[0046] Referring then to Fig. 8, a block diagram of a dual-chamber pacemaker **810** is illustrated. The pacemaker **810** is coupled to a heart **812** by way of leads **814** and **816**. The lead **814** has an electrode **815** that is in contact with one of the atria of the heart, and the lead **816** has an electrode **817** that is in contact with one of the ventricles of the heart. The leads **814** and **816** carry stimulating pulses to the electrodes **815** and **817** from an atrial pulse generator (A-PG) **818** and a ventricular pulse generator (V-PG) **820**, respectively. Further, electrical signals from the atria are carried from the electrode **815**, through the lead **814**, to the input terminal of an atrial channel sense amplifier (P-AMP) **822**; and electrical signals from the ventricles are carried from the electrode **817**, through the lead **816**, to the input terminal of a ventricular sense channel amplifier (R-AMP) **824**.

[0047] A control circuit or control system **826** controls the dual-chamber pacer **810**. The control system **826** receives the output signals from the atrial amplifier **822**, as well as the output signals from the ventricular amplifier **824**. The output signals at the outputs of the

atrial amplifier **822** and the ventricular amplifier **824** are generated each time that a P-wave or an R-wave, respectively, is sensed within the heart **812**. The control circuit or system **826** also generates trigger signals that are sent to the atrial pulse generator **818** and the ventricular pulse generator **820**. These trigger signals are generated each time that a stimulation pulse is to be generated by the respective pulse generator **818** or **820**. A stimulation pulse generated by the A-PG **818** is referred to as the "A-pulse," and the stimulation pulse generated by the V-PG **820** is referred to as the "V-pulse." During the time that either an A-pulse or V-pulse is being delivered to the heart, the corresponding amplifier, P-AMP **822** and/or R-AMP **824**, is typically disabled by way of a blanking signal presented to these amplifiers from the control system. This blanking action prevents the amplifiers **822** and **824** from becoming saturated from the relatively large A-pulse or V-pulse, respectively, that is present at the input terminals of such amplifiers during this time. Such blanking action also prevents the sensing of residual electrical signals that may be present in the muscle tissue as a result of the pacer stimulation, which sensing could falsely be interpreted as P-waves or R-waves.

**[0048]** Referring further to Fig. 8, the pacer **810** also includes a memory circuit **840** that is coupled to the control system **826**. The memory circuit **840** allows certain control parameters, used by the control system **826** in controlling the operation of the pacemaker, to be programmably stored and modified, as required, in order to customize the pacer's operation to suit the needs of a particular patient. Such data includes the basic timing intervals used during operation of the pacemaker, initial pacing rate, minimum pacing rate, and the programmed atrial escape interval. Further, data sensed during the operation of the pacer may be stored in the memory **840** for later retrieval and analysis.

**[0049]** A telemetry circuit **844** is optionally included in the pacer **810**. This telemetry circuit **844** is connected to the control system **826** to provide a data link external to the body. The telemetry circuit **844**, which is internal to the implantable pacer **810**, may be selectively coupled to an external programming device **848** by means of an appropriate communication link **850**, which communication link **850** may be any suitable electromagnetic link, such as an RF (radio frequency) channel or an optical channel. Advantageously, through the external programmer **848** and the communication link **850**, desired commands may be sent to the control system **826**. Similarly, through this

communication link 850 and the programmer 848 data (either held within the control system 826, as in a data latch, or stored within the memory 840) may be remotely received from the pacer 810. In this manner, non-invasive communications can be established from time to time with the implanted pacer 810 from a remote, non-implanted.

[0050] The pacer 810 in Fig. 8 may be embodied with any number of atrial pulse generators or ventricular pulse generators as suit the pacing needs of a given patient.

[0051] In accordance with an alternate embodiment of the present invention, the pacemaker 810 may further include one or more physiological sensors 852 (including physiological parameter sensor circuitry) that are connected to the control system 826. While the sensor 852 is illustrated in Fig. 8 as being included within the pacer 810, it is to be understood that the sensor may also be external to the pacer 810, yet still be implanted within or carried by the patient. A common type of sensor is an activity sensor, such as a piezoelectric crystal, mounted to the case of the pacemaker. Other types of sensors, such as physiologic sensors that sense the oxygen content of blood, respiration rate, pH of blood, and the like, may also be used in lieu of, or in addition to, an activity sensor. The type of sensor, if any, used is not critical to the present invention. Any sensor or combination of sensors capable of sensing body motion or a physiological parameter relatable to the rate at which the heart should be beating can be used. The use of such sensors makes the pacemaker rate-responsive, because the pacemaker adjusts the rate of pacing in a manner that tracks the physiological needs of the patient.

[0052] In one aspect of the invention, electrical stimulation is administered to the cardiac muscle. The anodal stimulation component of biphasic electrical stimulation augments cardiac contractility by hyperpolarizing the tissue prior to excitation, leading to faster impulse conduction, more intracellular calcium release, and the resulting superior cardiac contraction. The cathodal stimulation component eliminates the drawbacks of anodal stimulation, resulting in effective cardiac stimulation at a lower voltage level than would be required with anodal stimulation alone. This in turn, extends pacemaker battery life and reduces tissue damage.

[0053] In a second aspect of the invention, biphasic electrical stimulation is administered to the cardiac blood pool, that is, the blood entering and surrounding the heart. This

enables cardiac stimulation without the necessity of placing electrical leads in intimate contact with cardiac tissue, thereby diminishing the likelihood of damage to this tissue. The stimulation threshold of biphasic stimulation administered via the blood pool is in the same range as standard stimuli delivered directly to the heart muscle. Through the use of biphasic electrical stimulation to the cardiac blood pool it is therefore possible to achieve enhanced cardiac contraction, without skeletal muscle contraction, cardiac muscle damage or adverse effects to the blood pool.

[0054] In a third aspect of the invention biphasic electrical stimulation is applied to striated muscle tissue. The combination of anodal with cathodal stimulation results in the contraction of a greater number of muscular motor units at a lower voltage level, resulting in improved muscular response.

[0055] Having thus described the basic concept of the invention, it will be readily apparent to those skilled in the art that the foregoing detailed disclosure is intended to be presented by way of example only, and is not limiting. Various alterations, improvements and modifications will occur and are intended to those skilled in the art, but are not expressly stated herein. These modifications, alterations and improvements are intended to be suggested hereby, and within the spirit and scope of the invention. Further, the pacing pulses described in this specification are well within the capabilities of existing pacemaker electronics with appropriate programming. Accordingly, the invention is limited only by the following claims and equivalents thereto.